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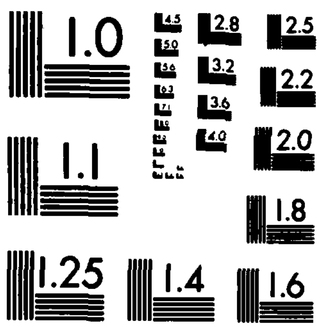
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PARAMETRIC ESTIMATES OF PROPULSION SYSTEM MAINTENANCE MANHOURS

THESIS

Timothy J. Sharp
GM-14

AFIT/GLM/LSM/84S-57

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PARAMETRIC ESTIMATES OF PROPULSION SYSTEM MAINTENANCE MANHOURS

THESIS

Presented to the Faculty of the School of Systems and Logistics

of the Air Force Institute of Technology

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Timothy J. Sharp

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Abstract

This ~~research~~ thesis investigated the potential of using cost-estimating relationships (CERs) to estimate aircraft maintenance manhour requirements for propulsion systems. The performance specifications and physical parameters of a large sample of USAF turbine engines were used to develop CERs. These CERs could be applied early in the life cycle of an engine in acquisition in order to estimate future maintenance requirements and effect design configuration changes.

The analysis was accomplished by the method of linear regression analysis of least squares. The CERs resulting from the regression were subjected to three tests to determine their predictive capability. A number of the CERs developed in the study displayed sufficient accuracy to be considered for application on acquisition programs.

PARAMETRIC ESTIMATES OF PROPULSION SYSTEM MAINTENANCE MANHOURS

1. Introduction

Overview

In 1981, Frank C. Carlucci, the Deputy Secretary of Defense, initiated 32 recommendations to improve the acquisition of weapon systems(6:1). The objective was to make the acquisition process more efficient, increase the readiness and sustainability of deployed weapons, and properly fund and budget for acquisition programs(6:2). The initiatives were begun in recognition of the inadequate readiness of American combat forces and inefficiencies in weapon system acquisition(7:16). The problems have caused severe shortages in funds for operations, maintenance, and readiness(12:26).

The United States Air Force (USAF) has been particularly hard pressed for funds to purchase spare parts and perform maintenance(7:16). Funding shortfalls have existed in the appropriate budget line items for many years, yet these maintenance and spare parts constitute a major portion of the operating and support (O&S) costs of a weapon system.

Further, O&S costs for a major weapon system over a 15 year life cycle are typically two to three times the acquisition cost of the system(19:28).

The USAF has continually underestimated its O&S funding requirements primarily because of poor estimates of system reliability and maintainability (R&M)(12:26). System R&M is commonly expressed in terms of the number of maintenance manhours (MMH) per system operating hour(3:84). MMHs must be accurately projected in order to budget for the proper level of support. Lieutenant General Hans H. Driessnack, Comptroller of the Air Force, has recognized the impact of inadequate funding levels due to poor R&M estimates and has stressed the need for improved projections(15:57).

Aircraft turbine engines are a promising area for improvement because of both the importance of the subsystem to mission success and the high acquisition and support cost(17:vi). Historically, propulsion systems have been the single aircraft subsystem with the highest O&S cost(17:4). One of the largest engine manufacturers in the world has identified fuel consumption and maintenance as areas of potential O&S cost reduction(20:1). We will leave fuel consumption to the design engineer

and focus on the area of projecting maintenance expenditures in terms of manhours.

Problem Statement

In the past, maintenance manhours, the largest O&S cost element, have been projected for propulsion systems through use of an engineering build-up approach where estimates of MMHs of significant components of the engine are aggregrated for the engine in total(10:100). This approach has consistently underestimated MMHs not only for engines but for other subsystems using this approach as well(12:26). It may be possible to use another approach to more accurately estimate the level of MMHs that will be experienced in the field(21).

Background

DOD Acquisition Process. The goal of the DOD acquisition process is to develop, procure, and field weapon systems capable of meeting operational requirements at the least total system life-cycle cost(9:3). To do this, a highly structured process was instituted by the DOD in the 1960's and 1970's. This process has been divided by regulation into the following four phases:

-Conceptual

-Demonstration and Validation

-Full-Scale Development

-Production/Deployment

Conceptual Phase. In the conceptual phase various alternatives capable of meeting the predetermined mission requirement are initially assessed. Alternatives explored normally include existing military and commercial equipment and new equipment designs. The goal of this phase is to eliminate infeasible concepts and select the most feasible concepts to enter the next phase of acquisition.

Demonstration and Validation Phase. The concepts selected for further study are intensely evaluated in the Demonstration (D&V) phase. Paper studies, initial hardware designs, and some breadboard prototypes are used to begin the transition from concept to hardware. Again as in the conceptual phase, the number of competing options are limited even further. At the end of this phase a small number of alternatives are selected to enter the next phase.

Full-Scale Development Phase. In the Full-Scale Development (FSD) phase the small number of chosen alternatives from the D&V phase are

completely developed and tested. Hardware is fabricated as identical as possible to the expected production design and tested against the projected mission duty cycle. At the end of this phase, the fully developed weapon or item is considered to be ready for production. A source selection at the conclusion of the FSD phase is normally held to determine which of the available weapons will be produced.

Production/Deployment Phase. The last phase of the acquisition process is the actual production of the selected configuration and delivery to the operational command. The user will operate and maintain the operational system in the field throughout its life until the system is eventually retired.

Literature Review

A number of studies have been conducted which bear on the problem of projecting MMHs for engines. Lynn M. Lynch and Neil V. Raymond studied the relationship between design variables of inertial measurement units and the O&S costs associated with maintaining these units. They hoped to prove their hypothesis that Cost-Estimating Relationships (CERs)

based on design variables could be used to make life cycle cost estimates. The authors concluded that use of CERs is a valid technique for estimating the life cycle costs of subsystems and components (14:53).

In 1976, Rodney W. J. Mullineaux and Michael A. Yanke completed a thesis on the estimation of jet engine life cycle costs. They concentrated on the cost estimating models used by the Air Force Systems Command (AFSC) and the Air Force Logistics Command (AFLC) to project acquisition and support costs. They concluded the current models were not effective because of the lack of historical O&S data required for input to the models(16:86-87).

Robert A. Breglio and Richard F. Wright attempted in 1977 to develop CERs for the overhaul cost of the engine core section based on both engine operating parameters and physical engine characteristics. The engine core section is the combination of the engine compressor and turbine. They met with limited success, concluding that CERs are appropriate in some, but not all, cases (5:58-59).

Another thesis in 1977 analyzed the sources

of information available for estimating operating and maintenance costs of turbine engines. Michael D. Baker and Bruce B. Johnston reviewed the Air Force data bases which contain O&S cost data to determine the usefulness of the data for O&S cost estimating. They found that the data available was useful but was not accurate enough for making precise life-cycle cost estimates(2:106-107). They also emphasized, as did Mullineaux and Yanke, the poor quality of the historical O&S data(2:101).

The approach contemplated for improving the estimating of propulsion system MMHs is developing CERs from either the engine physical characteristics, the engine operating parameters, or a combination of the two. Breglio and Wright found that use of a parametric CER can be very useful, particularly in the conceptual phase of an acquisition prior to the existence of detailed engineering drawings (5:10). Another advantage is that estimates can be made very quickly once a CER has been developed (9:10). Breglio and Wright stress the system for which the estimate is being made must be closely related in performance and design technology to the systems used to provide the estimating data

to ensure the accuracy and validity of the estimation(5:10).

Justification

An accurate technique for estimating propulsion system MMHs would be a useful tool for the USAF. Improved forecasting of engine MMHs could have a direct impact on the readiness and availability of USAF aircraft if engine requirements could be accurately projected, budgeted and funded, and the maintenance accomplished in a timely manner.

Accurate projections early in the acquisition of a program can influence design and provide significant life-cycle cost savings(4:51). Tradeoffs can be made during system design and development between R&M performance and system operational performance before the engine configuration is finalized(15:73). R&M improvements in the D&V and FSD phases can also preclude costly modifications after the equipment is in the field and the associated weapon system down time. The goal is to establish the maintenance level which gives the least maintenance cost for the level of system operation required(9:79).

MMH estimates have other uses as well. They are a key parameter in the maintenance plan established in the conceptual phase and published in the FSD phase. MMHs can project the proper numbers and skills of field and depot manpower needed to support the engine(3:238). Often, MMHs are cited as contractual requirements or goals, particularly in the FSD phase. MMH estimates are also used to develop Air Force Program Objective Memorandum budget requirements for maintenance funding.

Scope of the Research

There are a number of aircraft engine physical and functional performance parameters which might be useful in predicting MMHs. There are also other factors which may be pertinent to estimating MMHs.

The physical parameters include engine weight, diameter, length, and the number of stages in the compressor and turbine. These parameters describe the physical configuration of the propulsion system. They should be somewhat useful in estimating MMHs because of the impact the actual physical configuration will have on the R&M of the equipment(5:14). Previous studies have shown that propulsion system maintenance costs are generally less for engines of

simpler design(16:25,17:44). Each physical configuration parameter must be explored alone, and in combination with the others, to determine how useful these parameters are in estimating MMHs.

The functional performance parameters include engine thrust, temperature, pressure, airflow and fuel flow. Thrust is the measure of the force developed by the system. Specifically, such technical factors as the thrust-to-weight ratio, fan and compressor pressure ratios, air bypass ratio and turbine inlet temperature might be highly significant in parametric estimates of system MMHs. These key engineering and design parameters should exhibit high correlation to the level of MMHs experienced(21). Again, these parameters need to be analyzed alone and with the others to determine the strength of the relationship.

Last, there are several other factors not directly related to the specific engine design and performance which could correlate to MMHs. The mission and flight profile of the aircraft system in which the engine is installed could be somewhat significant. The length and cost of the engine development program could also be important. The maintenance concept employed on the engine could be

a factor. All of the aforementioned factors, physical, functional, and other, are probably worthy of careful study and analysis.

In order to limit the scope of this research effort, the study will encompass only selected turbofan and turbojet engines in the USAF inventory. Excluded are non-aircraft engines of all types and all turboprop and turboshaft engines. Turbofan and turbojet engines are selected because they are very important to strategic and tactical mission accomplishment and because they consume the majority of the USAF resources dedicated to propulsion systems (17:76).

This research will focus exclusively on the physical and functional characteristics of the selected propulsion systems and the relationship to MMHs. These characteristics should have the most direct relationship to MMHs and will be carefully evaluated.

A parametric approach of developing a CER to estimate subsystem MMHs has been found to have merit in other applications(14:51). It may be a useful technique to apply to propulsion systems. This technique would overcome the problem stated frequently of inadequate O&S cost data. It has been

proven that the major physical and functional characteristics of an item are good factors to consider in establishing CERs(5:59). This approach will be used to determine if CERs can be developed which are useful in estimating MMHs of selected types of propulsion systems.

Research Objectives

General. The general objective of the research is to investigate the relationships between the level of MMHs of propulsion systems and the functional and physical characteristics of the systems. The relationship will be used to develop an improved methodology for estimating MMHs.

Specific. The following specific objectives will be accomplished:

1. Document the physical and functional characteristics and the level of MMHs consumed by the selected engines.

2. Identify by type, by class, or in total any relationships that exist between the engine parameters and the MMHs.

3. Describe a CER which gives the best depiction of the noted relationship.

4. Document the possible utility of a CER method of estimating propulsion system MMHs.

Research Questions

To meet the research objective, the following specific research questions will be used to guide the research effort.

1. What are the functional and physical characteristics of the selected engines?

2. What is the historical level of MMHs consumed by these same engines?

3. What is the relationship, if any, between the functional and physical parameters and the level of MMHs?

4. What CER gives the best estimation of the relationship between the functional and physical parameters and the level of MMHs?

5. Would the estimation technique of a CER be useful in projecting future program MMH requirements and focusing design efforts?

II. Methodology

Overview

Estimates of cost or resource expenditures can be developed using several different methods. The major categories of methods are expert opinion, analogy, engineering, and parametric. Expert opinion is an appropriate method if historical data is not available to use the other three methods, if time constraints do not allow implementing other methods, or as a means to verify other estimates. The expert opinion method is considered inappropriate for this effort because data is available and time is not a limiting factor.

Analogy is a method of using known costs of a similar system as a basis to estimate the costs of a new system. Differences between the two systems are identified and the estimate adjusted as appropriate. Analogy is practical when a similar system exists; however, we desire a more generalizable, more scientific procedure.

The industrial engineering method has been

used as noted in Section I to estimate MMHs for engines for many years. This method has consistently underestimated MMHs and we have chosen to attempt to improve on this technique.

The final method, parametric cost estimating, uses system characteristics, or costs, to develop a cost-estimating relationship (CER). First, the dependent variable and a set of potential independent variables are defined. Data is then collected and analysis performed to determine the CER that best describes the data. The parametric estimate method has been chosen for this research.

The CER developed in the parametric estimate method has several advantages over the other methods. First, once the CER is developed and verified, it is simple and inexpensive to utilize in practical applications. Second, very little data on the new system is required to make an estimate. The major drawback can be the lack of predictive capability of the CER(14:7).

A CER is, in most cases, a fairly simple mathematical equation of the general form:

$$Y = b_0 + b_1 X_1 + b_2 X_2 + \dots + b_n X_n$$

where b_0 is a constant term and the coefficients, b_i, are defined in the derivation of the CER. To make estimates with the CER, values corresponding to the characteristics of the system whose cost is being estimated are substituted into the appropriate independent variable, X_i, and the resulting value of Y is the estimate.

Dependent Variable

The resource element chosen to be the dependent variable is MMHs. MMHs, expressed as a function of system operating hours, have been shown to be the best predictor of propulsion system O&S costs in studies performed by the Directorate of Propulsion Systems, Propulsion Systems Program Office, Aeronautical Systems Division(21). MMH data can be extracted from the Air Force 66-1 Maintenance Data Collection System, commonly known by its system designation of DO56. The DO56 system provides quarterly management reports which contain the required historical MMH data.

Independent Variables

Selection Criteria. Independent variables will be selected based on three decision rules, all of

which have to be met in order for the variable to be selected as a potential estimator for this research.

Decision Rule #1. The scope of this research has been limited to the functional and physical performance characteristics of some selected propulsion systems. Therefore, only those types of parameters will be candidates for selection.

Decision Rule #2. The variable should be a logically supportable estimator of costs(14:19). That is, the independent variables should be chosen on logical or deductive grounds because there is a perceived relationship between the variable in question and the dependent variable.

Decision Rule #3. The variable should be a characteristic of the propulsion system known or proposed early in the acquisition process, preferably in the conceptual phase. In order to make design tradeoffs and develop the logistic support system for the engine, the CER must be available early in the system acquisition. Hence, only characteristics known or proposed early in the development cycle are suitable as independent variables. This may limit the variables to the more important parameters of the engine.

Regression Analysis

Multiple regression analysis will be used to develop the CER through use of the ordinary least squares method. Regression analysis identifies potential relationships between two or more variables based on the input data. The regression analysis will be performed on the Digital Equipment Corporation VAX computer, located in the AFIT School of Engineering. The "S" statistics package, developed by Bell Laboratories and contained on the VAX operating system, will be the software programs used to run the analysis.

Statistical Tests

The resulting regression models, or CERs, will be analyzed using standard statistical tests. The coefficient of determination (R^2), the standard error of the estimate, an F-test on the overall regression and a t-test on the individual independent variables will be used to evaluate the statistical significance and the predictive capability of the CERs.

Coefficient of Determination. The coefficient of determination, R^2, is the ratio of variation about the overall mean which is explained by regression to

the total variation. The R^2 value will always lie between 0 and +1. The closer R^2 is to +1.0, the more variation is explained and the more acceptable is the model. While an R^2 of .70 is arbitrarily selected as the minimum value of acceptance, a larger R^2 is desireable.

Standard Error of the Estimate. The standard error of the estimate measures how well the CER fits the data. If the standard error of the estimate is relatively low when compared with the standard deviation of the cost data used, it indicates the CER fits the data and has successfully passed this test.

F-test on the Overall Equation. The overall significance of the CER will be tested by use of an F-test. Normally, a critical F-test is selected for multiple regression analysis based on the level of confidence desired for the equation. For this effort, a 95% confidence level has been selected. However, when CERs are to be used for predictive functions, an additional, more stringent test is often used(14:36). Therefore, the computed F-ratio for the equation must be greater than four times the critical F-ratio at the chosen 95% point in order to demonstrate statistical significance and predictive capability.

t-Test on the Coefficients. The significance of the coefficients of each variable in the CER will be tested with a t-test. A 95% confidence level is again chosen for statistical significance. Passing the t-test shows that the particular variable in question makes a significant contribution to the overall CER.

Predictive Tests

In addition to the statistical tests, the potential CERs will be evaluated using a number of test cases to determine the predictive capability of the CER. The test cases cannot establish the absolute predictive capability of the CER, but will be used to establish a relative measure for comparison of the CERs developed in the regression analysis. Test cases will be chosen which represent meaningful and demonstrative data points and cover a wide range of potential aircraft engine applications.

Summary

The research hypothesis will be considered to be supported if the CERs developed meet all of the preceeding statistical tests and display relative predictive capability. That is, the R^2 must be

greater than .70, the standard error must be relatively low, the overall F-test ratio must be at least four times the value of the critical, 95% level, F-ratio, and the individual coefficients of the independent variables must pass the t-test at the 95% confidence level.

III. Data Collection

Overview

In this section the first two research questions will be addressed. First, the selection of engines will be discussed. Then the physical and functional performance characteristics of the selected engines will be defined and the data collected to answer the first research question. To answer the second question, the historical level of MMHs consumed by these engines will be documented.

Selection of Engines

As previously stated, this study was designed to focus on selected turbojet and turbofan engines in the inventory of the USAF. Turbojet engines were originally designed in the mid-1950's and are still being produced today. Turbojets have a turbine-driven air compressor which supplies commpressed air to the combustion chamber and a discharge nozzle which directs the heated exhaust gases to the rear of the engine(8:15). Examples of turbojet

engines are the J57 engine and the J79 engine. Turbofan engines are of later design and are characterized by the use of a turbine which drives the fan and the compressor(8:47).

Engine developments occur over a period of many years, normally resulting in the production of several different, major configurations. These configuration changes are reflected in the designation of the type and model of the engine. In the case of turbojets, for example, the J57 is a type of engine and the J57-43 and the J57-59 are unique type-model configurations. An example of a turbofan would be the F100-100, where F100 is the type and -100 is the model.

The engines to be included in this study were selected by the author because of the large number of USAF aircraft flying hours they represent. The turbojet and turbofan engines selected are shown in Table I. These engines account for 80% or more of USAF flying hours on an annual basis. The only aircraft with flying hours of any magnitude not included are the C-130 and the T-33. The C-130 is powered by a turboprop engine and thus excluded and the T-33 will soon phase out of the inventory.

TABLE I

Selected Engines

Turbojet	Turbofan
J57-19/29	TF30-3
J57-43	TF30-7
J57-59	TF30-9
J60-3	TF30-100
J75-17	TF33-3
J75-19	TF33-7
J79-15	TF33-100
J79-17	TF34-100
J85-5	TF39-1A/1C
J85-21	TF41-1A/1B
	F100-100
	F100-200

Although these 22 engines were selected, not every air vehicle usage of the engine will be considered. The predominant usage of each engine type was obtained based upon data from the Maintenance Data Collection System, the D056 system, from January 1978 through December 1983. The resulting engine/airframe combinations which were used in the study are shown in Table II, on the next page. Two deviations from the procedure of selecting the predominant usage can be noted in Table II. Two applications of the TF30 engine, the F-111A and the F-111E, are included. Both were selected as in the six years of historical data, the flying hours for the two

TABLE II

Selected Engine/Airframe Combinations

Engine/Airframe		Engine/Airframe	
J57-19/29	B-52D	TF30-7	FB-111
J57-43	B-52G	TF30-9	F-111D
J57-59	KC-135A	TF30-100	F-111F
J60-3	T-39	TF33-3	B-52H
J75-17	F-106	TF33-7	C-141
J75-19	F-105	TF33-100	E-3A
J79-15	F-4D	TF34-100	A-10A
J79-17	F-4E	TF39-1A/1C	C-5A
J85-5	T-38	TF41-1A/1A	A-7D
J85-21	F-5E	F100-100	F-15A,B
TF30-3	F-111A	F100-100	F-15C
TF30-3	F-111E	F100-200	F-16A

programs are very similar in total. Two usages of the F100-100 are also apparent. Again, both are included because the flying hour programs for the A and B series of the F-15 and the C series of aircraft are very large and becoming less variable.

Collection of MMHs

Data to derive the dependent variable in the study, MMHs, was obtained from the DO56 system. The DO56 system is governed by AFM 66-1 and T. O. 00-20-2 procedures and contains data reported via AFTO form 349. The DO56 also receives aircraft utilization data directly from the AFR 65-110

system. A number of management reports are produced quarterly to fulfill various evaluation requirements. One of these, the B-25 report, (RCS: LOG-MMO(AR)7185) contains the MMHs and MMHs/flying hour (FH) for aircraft reported in the system. The report provides MMHs segregated by work unit code, by operating command, and separates the MMHs into the three levels of maintenance: organizational, intermediate, and depot. For this study, the man-hours per aircraft flying hour for organizational and intermediate maintenance were extracted for work unit code 23XXX, the code which represents the general engine workload. Depot MMHs were not considered in this study. Also excluded were incidental using command experience on the selected systems such as AFLC and AFSC test and evaluation operations. These operations are not considered to be representative of normal operational experience and represent only a very small percentage of the total flying hours. The MMHs per aircraft flying hours for the selected engine/airframe combinations are contained in the Appendix A. The MMHs per aircraft flying hour were then adjusted to MMHs/engine flying hour (EFH) by dividing by the number of engines per aircraft application.

A weighted average MMH/EFH was then computed for the six years of historical data for each of the 24 combinations. The final composite MMHs/EFH for 1978-1983 for utilization as the dependent variable are displayed in Table III. The intermediate calculations discussed herein are also contained in Appendix A.

TABLE III

MMHs/EFHs

CY 1978-1983

Engine	A/C	MMH/EFH	Engine	A/C	MMH/EFH
J57-19/29	B-52D	.52	TF30-7	FB-111	2.11
J57-43	B-52G	.50	TF30-9	F-111D	1.73
J57-59	KC-135A	.37	TF30-100	F-111F	1.52
J60-3	T-39	.51	TF33-3	B-52H	.34
J75-17	F-106	2.17	TF33-7	C-141	.65
J75-19	F-105	3.17	TF33-100	E-3A	.17
J79-15	F-4D	1.26	TF34-100	A-10A	.57
J79-17	F-4E	1.13	TF39	C-5A	2.18
J85-5	T-38	.69	TF41	A-7D	1.29
J85-21	F-5E	1.43	F100-100	F-15A,B	1.82
TF30-3	F-111A	2.31	F100-100	F-15C	1.56
TF30-3	F-111E	2.11	F100-200	F-16A	1.94

The six years of flying of these selected engines represents over 11,500,000 hours of aircraft usage. Individual aircraft usage over the total period ranges from just over 100,000 hours for the F-105(J75-19), for all the F-111 models(TF30s), and

the E-3A(TF33-100), to over 2,000,000 hours for the T-38(J85-5), and over 1,000,000 hours for the KC-135A(J57-59) and the C-141(TF33-7). These large numbers of hours of operation make the composite MMH/EFH figures very significant and tend to remove any bias or error because of the large data sample size. This is not to say that the DO56 does not contain at least some normal amount of error. It should indicate, however, that the relative error from sample engine to sample engine should be stable and at some relatively constant level.

The resulting MMH/EFH figures become the dependent variable for the study. The lowest figures are indicated for the TF33-100, the TF33-3, and the J57-59. This is to be expected because of the less damaging mission and longer mission length of the E-3A, the B-52H, and the KC-135A, respectively, in comparison to other mission types. It is also notable that the lowest MMHs are achieved on aircraft that have very high and very low flying hour programs. The highest MMHs were expended over the data period on the J75 engine models, the TF30 engine models, and the TF39 engine. The J75 engines are both old, single engine applications which helps explain the high ratio. The TF30 engine family has

been plagued by technical problems since its introduction into the active inventory. These technical problems in conjunction with the low utilization rate of the F-111 series aircraft probably account for the high MMH/EFH. The TF39 has also had a number of reliability problems which could be the major cause of its high composite number.

Selection of Independent Variables

Several independent studies have been performed that have identified major cost-driving variables for turbine engines(5,16,17). These research efforts analyzed the impact of over 30 separate, distinct variables on the cost of acquiring and supporting propulsion systems. The majority of these variables were of the functional performance and physical characteristic type as has been defined in this research. These variables were reviewed with expert logistics engineers and cost analysts to develop a set of independent variables for study(1,13,18,21). The three decision rules specified in Section II were used in conjunction with the expert opinion to limit the large number of potential variables to a more meaningful and practical number. Other propulsion cost studies done in the past have used a large set of

variables; one study used 27 and another used 24 (5,16). Review of the results of these studies seems to indicate that a smaller subset of variables is sufficient for constructing CERs for estimation purposes. The twelve independent variables chosen are shown in Table IV.

TABLE IV

Independent Variables Selected

Variable Name	Variable
X1	Maximum or Military Rated Thrust
X2	Maximum or Military Specific Fuel Consumption
X3	Maximum or Military Turbine Inlet Temperature
X4	Normal Rated Thrust
X5	Normal Specific Fuel Consumption
X6	Airflow
X7	Compressor Pressure
X8	Weight
X9	Length
X10	Diameter
X11	Compressor Stages
X12	Turbine Stages

The first seven variables are functional performance characteristics of the engines. The maximum rating apply to the turbofan engines and are equivalent to the military ratings for the turbojet engines. The normal ratings are the same performance

point for both types of engines. The last five are the physical characteristics of the engines chosen for the study. Contained in Appendix B is the data for all the independent variables for each of the 24 engines. The data was extracted from the "Engine Handbook," an annual publication of AFLC/LOE, which contains technical, performance, and management data on all engines in the active Air Force inventory(8).

IV. Data Analysis and Findings

Introduction

In the last section, the first two research questions were answered. In this section, the third and fourth research questions will be addressed. First, an attempt will be made to establish the relationship, if any, between the physical and functional parameters of the selected Air Force engines and the level of MMHs consumed in the field. Then, if possible, CERs will be developed which give the best estimation of the relationship between the parameters and the level of MMHs. To do this, the entire data set of the 24 engines and the 12 variables will be analyzed through use of the linear regression technique discussed in Section II. Then, various subsets of the complete variables set and of the complete engine sample will be tested independently to establish the sensitivity and predictive capability of more specific data subsets.

Complete Data Set

A stepwise regression was performed using all the independent variables and the complete engine data sample. The stepwise regression evaluates all of the possible variable combinations and screens them to identify the most statistically significant. The analysis first identifies which of the first order predictors of the dependent Y variable is the most significant. Then, the best second order combination is flagged and the program continues until the entire independent variable set is reached. This stepwise regression is known by the command of "Leaps" on the "S" statistics package. For the initial analysis, the best relationship of each level or order was identified and regressed individually against the MMH/EFH dependent variable. The effect of adding terms of increasingly less statistical significance should be apparent when the regression results are tabulated. There may also be a point reached where the addition of terms does not improve the significance of the equation but, in fact, decreases its power. The complete results of the regression of the selected variable combinations are contained in Appendix C. Table V summarizes the results of the complete data set regression.

TABLE V

Complete Data Set Results

Name	Variables	R^2	Std.Error	F
X09	X9	.59	.52	31.58
X11	X9,X11	.68	.47	22.72
X21	X9,X11,X12	.76	.42	20.78
X31	X9,X10,X11,X12	.77	.42	15.64
X41	X2,X8,X10,X11,X12	.84	.36	18.52
X51	X4,X8,X9,X10,X11,X12	.85	.36	16.08
X61	X1,X4,X6,X9,X10,X11, X12	.87	.35	15.18
X71	X1,X4,X6,X7,X8,X9, X11,X12	.89	.33	15.19
X81	X1,X2,X4,X6,X7,X8, X9,X11,X12	.90	.32	14.09
X91	X1,X3,X4,X5,X6,X7, X9,X10,X11,X12	.91	.32	12.60
X101	X1,X2,X3,X4,X5,X6, X7,X9,X10,X11,X12	.91	.33	11.10
X111	X1,X2,X3,X4,X5,X6,X7, X8,X9,X10,X11,X12	.91	.34	9.49

As can be seen, the R^2 scores are high, ranging from .68 to .91. The standard error is also relatively high, with a range of .32 to .47. The F-test on the overall equation also exhibits a large range of scores with decreasing values as the number of variables increases. These results indicate initially that the statistical relationship is a relatively good one. The R^2 scores are particularly encouraging. The trends in data with increasing R^2 scores, and decreasing standard error

and F-test as the number of variables increases are also what would be expected.

Each of the potential CERs from the complete data set were subjected to the four statistical tests outlined in Section II. To review, the CER must pass all four tests in order to support the research hypothesis. Table VI contains the results of the tests on each proposed CER.

TABLE VI

Complete Data CER Tests

CER	R^2	Std.Error	F	t	Score
X09	-	-	+	+	++
X11	-	-	+	+	++
X21	+	-	+	+	+++
X31	+	-	+	-	++
X41	+	+	+	+	++++
X51	+	+	+	-	+++
X61	+	+	+	-	+++
X71	+	+	+	+	++++
X81	+	+	+	-	+++
X91	+	+	+	-	+++
X101	+	+	+	-	+++
X111	+	+	-	-	++

Key: + pass
- fail

Review of the test results shows all of the CERs pass at least two of the tests. Several CERs pass three tests, but fail one test. Of those that

pass three tests, all fail the t-test for significance of individual variables except for CER X31. X31 fails the standard error test although not by a large margin. Only two CERs, X41 and X71, pass all the four tests. X41, containing the variables X2, specific fuel consumption (SFC), X8, weight, X10, diameter, X11, compressor stages, and X12, turbine stages, passed all the tests easily. The CER X71 contains the variables X1, maximum thrust, X4, normal thrust, X6, airflow, X7, compressor pressure ratio (CPR), X8, X9, length, X11, and X12. X71 also passed all tests by a wide margin except for the t-test on variable X8. Variable X8 was only .006 outside the critical range of values for the t-test on individual variables. X41 does exhibit some unwanted correlation between the diameter and turbine stages variables. X71 also has undesireable correlation, the worst case being between airflow and turbine stages.

Both CERs X41 and X71 were subjected to a number of individual tests to establish the predictive capability of the CERs. Each was first used to estimate MMHs for the F-15 engine using the known functional and physical parameters of the engine. X41 CER estimated the engine to require 2.874 MMHs/EFH

while X71 estimated 1.883 MMHs/EFH. The actual composite MMH/EFH has been shown to be 1.82. Therefore, X41 overstated the estimate by just over one manhour per engine flying hour, or 58%. X71, however, estimated the requirement to be 1.883, an overstatement of just slightly over 3%.

A further test case was used to compare the predictive capability of both CERs . The case is a new production engine with minimal flight test and operational experience. The F101 engine on the B-1B aircraft was chosen for this estimation. The physical and functional characteristics of the F101 are displayed in Appendix B for informational purposes. The values of the F101 are considered to be well established by the USAF in conjunction with the prime engine contractor. Here then, we have a case of an engine with definitive functional and physical parameters but with essentially no operational history. X41 CER predicted the F101 would consume 3.410 MMHs/EFH, well above the range of the current USAF estimate which is 1.1 - 2.0(20). X71 CER estimated a ratio of -1.932 MMHs/EFH. A negative value of MMHs is, of course, clearly not feasible.

As a final test of predictive capability, a nominal engine characteristic was developed based upon

the mean value of each independent variable. This nominal engine could then be used to compare CER estimations with the average dependent variable for the 24 aircraft/engine combinations in the study. The average MMH/EFH figure was computed to be 1.335, with variation of .64. X41 CER estimated the nominal engine to require 2.661 MMHs/EFH and X71 CER estimated the number to be 1.537. Thus, X41 doubled the requirement but X71 was only 15% over the nominal mean value. Test results are contained in Appendix D.

These tests were performed to test the sensitivity and predictive capability of the proposed CERs. The F100 engine test represented an example of a high thrust, low weight, turbofan engine. The F101 was an example from the other extreme of engine design, being a heavy weight, large air bypass engine. The nominal engine represented a composite average to give an additional comparison of the two CERs.

It is apparent that while both the X41 and X71 CERs are statistically significant based on the four tests performed, they may lack predictive capability. One method used in previous studies to determine engine CER predictive capability has been used here (5:25). Sample engines were used to make estimations

and the percent predictability was computed. The average predictability for the three tests of F100, F101, and nominal engine could be obtained for each potential CER and compared to determine the CER having the most predictive power. The X41 CER had an average predictive capability in the three tests of 92.3%; the X71 had 81.0%. Such poor predictive capability makes these CERs inadequate for the estimating accuracy desired. The maximum acceptable predictability level of 50% will be used henceforth with a lower percent as being desireable.

Other studies have found that a large R^2 value can be attained by introducing a large number of variables into the CER model, each with insignificant marginal contributions to the equation(5:61,16:67). However, the model may have virtually no predictive capability. One study of aircraft engine jet overhaul costs had a R^2 range of .69 - .99 but a percent predictability of between 54% and 289%(5:77). The result of the testing of the CERs from the complete data set shows similar findings, high correlation and data fit but very poor capability to make accurate estimations. The number of independent variables was purposely limited in this study in an attempt to preclude this occurring, to no avail.

Reduced Variable Data Set

It is apparent from testing of the CERs developed from all of the available twelve variables that a reduced number of variables may provide improved results. To analyze this interim finding, the complete variable set will be divided into two subsets and each reduced subset tested separately. It is most logical to separate the variables into the categories of functional performance characteristics and physical characteristics. The functional characteristics are X1 through X7, inclusive, as identified in Table IV. The physical characteristics are X8 through X12, also inclusive. These two groups will be analyzed using the same methodology and tests as were used with the complete data set and the results compared.

Functional Performance Variables. The functional performance variables were analyzed in conjunction with the complete engine sample using the standard multiple linear regression technique. The results of the most significant relationships are shown in Table VII, displayed in the same format as the previous results. Seven potential CERs resulted because of the use of the seven variables.

TABLE VII

Performance Set Results

Name	Variables	R^2	Std.Error	F
X02	X2	.43	.61	16.81
X24	X2,X4	.70	.46	24.71
X126	X1,X2,X6	.71	.46	15.94
X1237	X1,X2,X3,X7	.73	.46	12.76
X12347	X1,X2,X3,X4,X7	.73	.47	9.70
X123567	X1,X2,X3,X5,X6,X7	.74	.48	7.92
XXX	X1,X2,X3,X4,X5,X6 X7	.74	.49	6.48

These potential CERs were then subjected to our four statistical tests. The results are shown in Table VIII. The complete regressions are shown in Appendix E.

TABLE VIII

Performance Data CER Tests

CER	R^2	Std.Error	F	t	Score
X02	-	-	+	+	++
X24	+	-	+	+	+++
X126	+	-	+	-	++
X1237	+	-	+	-	++
X12347	+	-	-	-	+
X123567	+	-	-	-	+
XXX	+	-	-	-	+

Key: + pass
- fail

While none of the proposed CERs passed all four of the tests, two interesting items appear. All of the CERs pass the R^2 test except the X02 CER which consists of only the X2 variable. The R^2 scores, however, of the other CERs are all tightly grouped in the low 70's. All of the seven CERs fail the standard error test, many by a wide margin, indicating a poor fit between the data and the CER.

CER X24 is the only potential one that passes three of the tests and will be evaluated further. This will be done even though it violates the rule of having to pass all four tests, in order to determine if statistical accuracy should not be sacrified for other factors. X24 will be used to estimate the MMH requirements for the three sample cases already available to calculate its predictive capability.

Using this simple two variable CER of maximum SFC and normal thrust appears to yield very acceptable results. X24 estimates the F100 engine MMHs to be 1.784, against an actual of 1.82. It predicts F101 MMHs to be 2.429, versus a projected range midpoint of 1.55. Last, X24 estimates the composite nominal engine to require 1.324 MMHs/EFH, against an average figure of 1.335. The CER's overall predictive capability based on the three tests is

computed to be 20%, well below the 50% maximum acceptable limit. Test cases are shown for X24 in Appeneix F.

CER X24 appears to be a better CER than any of the CERs derived from the complete data set. It seems to indicate that the four statistical tests give only the strength of the correlation and do not in any way measure the prediction power of the CER in question. X24 has excellent predictive capability even though it has relatively high standard error. X24 has an additional advantage in consisting of only two variables. It would not be time or resource consuming to make estimations with this simple CER.

Physical Characteristic Variables. A second set of reduced variables will be subjected to the same analysis that has been previously accomplished on the performance variables. This second subset is the variables of physical characteristic, X8 through X12. These characteristics are engine weight, length, diameter, and the number of turbine and compressor stages. The results of the regression of the physical variables will be compared to the performance results to see which subset yields the better CERs. The results of the regression of the physical variables are shown in Table IX.

TABLE IX

Physical Set Results

Name	Variables	R^2	Std.Error	F
X09	X9	.59	.52	31.58
X911	X9,X11	.68	.47	22.72
X912	X9,X11,X12	.76	.42	20.78
X912a	X9,X10,X11,X12	.77	.42	15.63
XX4	X8,X9,X10,X11,X12	.84	.37	18.33

The five best relationships exhibit a wider range of R^2 scores and standard error when compared to the performance variable subset. However, the statistical tests show variation in the favorable direction of high R^2 and low standard error. This subset also appears to compare favorably with the best relationships from the complete data set. This could be expected because four of the five variables of X41, the best CER from the complete data set, are physical variables as are four of the eight variables of X71, the next best complete data CER. These regressions are also in Appendix E.

These five potential CERs were then evaluated using our standard test criteria. We would expect the tests on these potential CERs to be more favorable than the tests on the performance subset. The best CER from that data set could pass only three of the four tests. The results are shown in Table X.

TABLE X

Physical Data CER Tests

CER	R^2	Std.Error	F	t	Score
X09	-	-	+	+	++
X911	-	-	+	+	++
X912	+	-	+	+	+++
X912a	+	-	+	-	++
XX4	+	+	+	+	++++

Key: + pass
- fail

As expected, the physical variables exhibit improved test results over the performance variables. Here, XX4, the CER containing all of the physical variables, passed all four of the tests and another relationship, X912, passed three of the four tests. XX4 will be used to estimate the MMH requirements of the three sample cases to determine its possible utility as a predictor.

CER XX4 estimates the first case, the F100 engine, to require 1.84 MMHs/EFH. Further, it estimates the F101 engine requirement to be 1.11 and the composite engine to be 1.30. These estimates are very close to what would be expected and it is not at all surprising to find that as surmised

the CER's predictive capability is computed to be 11%, far better than any previous estimator. The CER that has shown the next best predictive capability, X24, was computed to be 20%. While X24 does not display the accuracy of XX4, it may have a slight advantage in consisting of only two variables as versus the five variables in XX4. This advantage, however, may not be great because the variables in XX4 are usually well-known early in the acquisition cycle of an engine or can be accurately forecast by the design engineers. In fact, all of the physical characteristics may be easier to establish early in a program's life cycle than any of the more complex performance parameters. If this is true, the five variable physical estimator, XX4, would probably be available to make estimates prior to the smaller, two variable, performance-based estimator, X24. Test cases for XX4 are again shown in Appendix F.

Reduced Samples

A number of other tests were run to determine if a more specific sample other than the general sample of all 24 engines would improve the capability to estimate. These reduced samples were performed using the entire set of all twelve independent variables. First, the total sample size of 24 engines

was divided by type of mission. Two categories were established by similarity of mission; fighter, attack, and trainer aircraft engines in one category and the bomber, cargo, and tanker aircraft engines in the other category. The category of fighter, attack, and trainer aircraft engines was chosen for evaluation because of its larger sample size. The best relationship that could be developed from this reduced sample, named b41, used the variables X1, X3, X4, X9, and X11. This is the first occurence of the variable X3, turbine inlet temperature, in any of the CERs rated as best in their group. This CER, like only X71, has an equitable mix of variables from both the performance and physical parameter groups. CER b41 has an R^2 score of .95 and a relatively low standard error percentage of 17. In addition, it had favorable F and t test results. Although b41 passed all four of our statistical tests, its predictive capability as measured by the F100 test case was only 51%. The MMHs requirement for the nominal engine composite was also computed. b41 estimated the requirement to be 2.912, an overstatement of 118%. It should be expected that the CER developed from the fighter, attack, and trainer aircraft engines would give better

estimates for engines in that category than other engines. We find this to be true. It is also apparent that a CER which consists of variables from both the performance and physical groups of variables yields intermediate results. This indicates a reduced engine subset of specific mission may outperform CERs developed from the complete sample but only when all performance and physical variables are used. When only the performance or only the physical variables are used, the complete sample of engines giver superior results.

Another reduced sample test was run by dividing the total sample by company of manufacture. The largest sample, those engines designed and produced by the Pratt & Whitney Aircraft Division of United Technologies Corporation, was chosen for evaluation over the General Electric Company sample or the single General Motors Detroit Diesel Allison engine. The most significant relationship, d41, consisted of variables X1, X4, X9, X10, and X11. All of these variables have appeared in previous CERs. d41 had a high R^2, .97, and a low standard error, .17. This CER also had significant t and F test scores and thus passed all four of the statistical tests.

This sample of Pratt & Whitney Aircraft engines

had all of the mission types represented. There were fighter and trainer engines as well as bomber, cargo, and tanker engines in the sample. Therefore, d41 CER was evaluated against all three of the test cases used previously. d41 estimated the F100 MMH requirement to be 1.8602, versus an actual six year average of 1.82, or within one percent. The F101 engine on the new bomber was computed to be 1.9271, against the current midpoint forecast of 1.55. The nominal composite engine characteristic was estimated by d41 to be 1.3302, exceptionally close to the composite average of 1.335. The average predictive capability for the three tests is 8.7%, which exceeds the previous best. It is interesting to note that the d41 CER, which was developed from Pratt & Whitney Aircraft data, displayed the poorest predictive capability when used to estimate the requirements for a competitor's engine. Complete regressions and test cases for these reduced samples are shown in Appendices G and H, respectively.

Summary

The objective of this research was to develop CERs to estimate MMHs for engines based on their performance specifications and physical characteristics. Five different combinations of the engine sample and the independent variables were tested to

develop CERs. First, the complete variable set was placed in combination with the complete engine data sample. The best CERs developed in this initial test were statistically significant but lacked the predictive capability desired for practical application.

Next, the complete engine data set was analyzed using only the set of functional performance variables. While the most statistically significant CER from this effort could not pass all four of the tests, it did exhibit greatly improved predictive capability. When only the physical variables were used in conjunction with all the engines in the sample, an excellent CER was developed. The CER was statistically significant and appeared to be an excellent predictor of MMHs.

Last, further tests were accomplished using all the variables available but only selected, more specific engine samples. The first of these reduced engine samples, fighter, attack, and trainer engines, produced a CER that was statistically significant but provided estimations on a level equal to the ones occuring with the complete engine and variable data. The second of these tests, the reduced sample of Pratt & Whitney engines, developed a CER which was statistically significant and provided superior estimations as measured by the three test cases.

It is apparent that several of the independent variables do not make a meaningful contribution to the estimation of MMHs. Normal fuel consumption, designated as X5, was not included in any of the better CERs developed in the regression analysis. Three of the variables, X3, turbine inlet temperature, X6, airflow, and X7, compressor pressure, were only included in a single evaluated CER. This is indicative of a very weak statistical relationship. In fact, X6 and X7 were both included as variables in the X71 CER, which was clearly not an outstanding estimator. On the other hand, two of the physical variables, X9, and X11, were each included in four of the six CERs evaluated in-depth. This is probably because of the linear relationship of these two variables to MMHs more than the direct causality of the relation. That is, the length and number of compressor stages may not have the most direct causality in the relationship to MMHs, but do have an excellent statistical relationship. Certainly some of the performance variables of thrust, temperature, and pressure would be considered to be more significant cost drivers than would some of the physical variables.

This research has met that portion of the objective which was to develop CERs based on engine physical

characteristics and performance parameters. Other similar, past efforts to develop meaningful CERs for propulsion systems were also successful in this regard(5:57). While the findings indicate that both the performance and physical variables are useful in developing CERs, the physical variables predominate in the better CERs. The higher R^2 scores and the lower error of the CERs based only on the physical variables indicate the greater statistical significance of this group. In addition, it was found that smaller subsets of the engine sample can be useful in specified applications.

V. Conclusions and Recommendations

Overview

The objective of this research was to investigate the relationship between the level of MMHs of propulsion systems and the physical and functional characteristics of the systems. The fifth, and last, research question to be answered will be addressed in this section. Restating the question, could the estimation technique of a CER be useful in projecting future program MMH requirements?

After providing an answer to this critical question, a number of recommendations are provided to focus this research to achieve more practical application and guide future research.

Conclusions

Review of the available research and personal interviews conducted with knowledgeable personnel indicated that there was no systematic, quantifiable technique being used early in the engine acquisition cycle to estimate MMH requirements. Further, it was

clear that a need exists for development of a technique to make more accurate projections before detailed engineering information is available. This is especially true with the additional emphasis being placed on life-cycle costing and specifically, on operating and support costs in weapon system acquisition. CERs have been found to be a useful technique for cost estimating on other commodities and have been applied here to propulsion systems. The expertise and capability also exists within the USAF to develop and utilize CERs to estimate MMHs.

A number of researchers have indicated that CERs require valid historical data to construct meaningful relationships(2:34,5:61,16:44). There is a wealth of engine information available in the various Air Force management and maintenance data collection systems which could be used to construct CERs. The validity of any data is always subject to question but the relative accuracy and the statistical significance of the voluminous data used in this research is apparent. The statistical validity of the CER technique has also been well documented over the last thirty years and cannot be questioned.

The CERs developed in this research tend to indicate a number of conclusions. It was found that CERs

constructed from the complete engine sample and the entire variable set had high statistical significance but poor predictive capability. As previously stated, other research has found this to be true in other applications as well as with engines. Statistical significance, thus, must be viewed as desireable but not as completely necessary. CERs should not be discarded because of low significance without an additional analysis to determine the predictive capability of the CER. To demonstrate this conclusion, one of the CERs developed in the research was able to pass only three of the four statistical tests yet outperformed CERs which had passed all four tests in estimation accuracy.

It is also apparent that CERs constructed from only a subset of the independent variables provided better estimations than did those from the complete variable set. In both cases, the entire engine data sample of all 24 data points was used. In both the cases shown the relationships were not as statistically significant. However, the estimation accuracy of the MMHs was almost an order of magnitude improvement over the complete independent variables prediction. While one might intuit that the performance variables should be more significant in projecting maintenance requirements, it was found that the physical characteristics

provided CERs with improved predictive capability in this study. Again, physical variables may not have the most direct causality to MMHs, but surely have more significant statistical relationships.

Two reduced engine samples were also analyzed as were reduced variable sets to determine the utility of such an approach. Here the entire independent variable set of twelve variables was used. The first sample was the fighter, attack, and trainer aircraft engines; the second sample was the Pratt & Whitney engines. In both samples, there was high statistical significance as evidenced by the high R^2 scores and the low standard error. The CERs produced had the highest statistical significance of any in the research. However, the CERs had very different predictive capability. The best CER from the first sample could estimate no better than the original CERs from the entire variable and engine data sets. The estimations made by the best CER from the second sample, on the other hand, were superior to all the other CER estimations in the research. It can be concluded that CERs produced from more specific engine samples can yield superior estimations to those made from CERs developed from more general engine samples. Caution must be taken when working with reduced samples as results were shown to be mixed.

There appears to be an inverse relationship between R^2 scores which measure the data fit and the predictive capability of the CER. Normally, the higher the R^2 score, the better is the predictive capability of the relationship. Breglio and Wright and Mullineax and Yanke also encountered this phenomenon in their research(5:59,16:75). The cause here is unknown. It may be due to the use of linear regression techniques where non-linear relationships exist or may be caused by the use of variables which have weak or nonexistent causality.

The engine sample and the variable set chosen certainly have influenced the results. This is most apparent in noting that the F101 engine test case results were the worst of the three test cases for every CER evaluated. The data base may be biased against large turbofan engines or against General Electric Company engines or against bomber, cargo, and tanker engines in some way. The data base was purposely designed to be representative of the Air Force active inventory but was not conceived in any other regard.

Similarly, confidence levels about the mean of the estimated MMHs have not been constructed because we have not attempted to conclusively demonstrate the

absolute validity of the data base. The data base used in this research is believed to be reasonably accurate and is available for application consistent with the constraints previously documented. It has been shown that smaller subsets of data can provide both more and less accurate CER estimates. The confidence level provides only an estimate of the sampling error and is not an accurate method to judge the validity and capability of a CER.

Based upon these conclusions, the last research question posed can be answered. That is, can CERs be developed which could be useful early in a program life to estimate MMHs for engines? The CERs developed in this research have been shown to have varying degrees of statistical accuracy and predictive capability. The better CERs obtained from the data base constructed for the study meet all the test criteria and appear to have merit for potential application. The situation exists where this data base can also be modified as desired to perform sensitivity analysis and provide even more accurate estimates given the availability of resources and time to perform the analysis.

The CERs developed here have all the advantages described in Section II of being simple and inexpensive

to use in practical applications. Additionally, CERs relying on only performance or only on physical variables have been provided for use in situations where only limited information is available. More importantly, the CERs appear to have excellent predictive capability, overcoming the major problem of the CER technique. The CERs developed in this study, and others which could be easily constructed using the existing data base, could be made early in the life cycle of an engine. Even in the conceptual phase of the development process, some general information is usually available as to the desired performance specifications and physical configuration of the engine. Certainly in the demonstration and validation phase such information exists. Later, during the full-scale development of the engine, the initial CER estimates can be compared with the detailed engineering estimates and deviations noted and analyzed.

It can be concluded that the objective of this research has been met in total. The physical and performance characteristics of a large sample of Air Force engines have been documented. A data base of six years of operational experience has been used to construct the MMH consumption history for the engine sample. The relationship between the MMHs and the

engine variables has been described by the development of potentially useful CERs. These CERs were evaluated to determine which provided the best estimation of MMHs/EFH. Last, the issue of utilization of CERs to estimate MMHs early in an engine acquisition was discussed. It was shown that the CER technique is valid and could be useful for making estimations of propulsion system MMH early in the acquisition cycle.

Recommendations

A number of recommendations can be made based on this research. When an estimate of MMHs is required for a new propulsion system, the CERs developed in this study should be considered for application. Two excellent CERs are available which are based on different functional performance and physical characteristic variables and can be used simply and quickly. Another outstanding CER has been developed based on a smaller sample of engines which may provide even more superior results on selected applications. The estimations made by these CERs can be compared with any other available estimates and conclusions drawn. The earlier the estimate is made, the more useful is the CER technique. The CERs and the data base produced in this study should be made available to the propulsion acquisition community

in the Air Force for their critical review and application on new and existing programs.

This CER technique may also have merit for estimating MMHs for systems or subsystems other than engines. The data should be available to develop CERs from the same sources as were tapped in this study for many other items and commodities. The same benefit of early and accurate estimation of MMH requirements is applicable to other items as well as to engines. Accordingly, this research should be provided to all the USAF system program and item procurement offices at the product divisions of AFSC. It should also be provided for informational purposes to the staff agencies and organizations that support the acquisition functions because of the applicability to all functional areas.

Early estimates of MMH requirements should be required by high level DOD and USAF management because of the large impact of maintenance on downstream O&S costs. MMHs should be highlighted in appropriate presentations and program reviews and should be a critical design specification.

In addition to the practical utilization of this research within the Air Force, the other services may be able to apply this technique to their

acquisition programs. The Navy, in particular, because of their procurement of turbine engines, should be provided this research for their review and use .

Further Research Needs

Several other aspects of propulsion system MMH estimation not covered in this study should be examined. First, this study focused on MMHs consumed in the field. Depot level MMH requirements were not considered in order to limit the scope of the research. Other research should be accomplished to pursue depot level requirements and the interaction between the field and depot level expenditure of manhours.

Second, other independent variables are worthy of study. This effort used only selected performance and physical variables and excluded all other types of variables. Other performance and physical variables should be evaluated. Such variables as maintenance concept and resources consumed in the engine development program may also be highly correlated to MMHs.

Third, the level of detail for this study was at the whole engine level. This was done because the available data was aggregrated at this level. It may be possible to document data at the subsystem level and perform an analysis at the first indenture level.

MMH requirements defined at the engine subsystem level could be very useful in focusing design efforts and determining specific manpower and equipment requirements. Total engine subsystem data is not currently available in Air Force data systems to support such research but is available for some selected work unit coded subsystems.

Fourth, the relationship assumed in this research between MMHs and the engine characteristics was linear in every case. The relationship of some variables could, in fact, be non-linear. Further study could be done to determine what type of relationship actually exists for each variable.

Last, other data bases of different sample size have been shown to be useful in making more accurate estimations. The data base derived for this research was based on a simple, one dimensional premise; to mimic the current Air Force turbojet and turbofan inventory. More sophisticated data bases could be investigated for specific applications capable of making outstanding estimations.

In summary, the entire area of cost estimating within the DOD is a fruitful area for research. USAF engines, because of their large consumption of resources, the availability of useable data, and the

importance of their serviceability to mission success, are a particularly viable area for study. Research such as this will, hopefully, provide some improvement over existing methods in the management of resources and improve the operational capability of our combat forces.

Appendix A: MMHs/EFHs Derivation

MMHs/Aircraft Flying Hours

							CY
Aircraft	Engine	78	79	80	81	82	83
B52D	J57-19/29	5.49	4.82	4.72	3.35	1.42*	.72*
B52G	J57-43	4.83	3.79	3.60	1.11*	3.77	3.94
KC135A	J57-59	3.07	2.88	2.88	.38*	2.95	3.02
T39	J60-3	1.31	1.20	.68	.94	.93	1.06
F106	J75-17	2.20	2.16	2.06	1.96	2.16	2.58
F105	J75-19	4.21	2.60	4.12	2.23	2.03	.91
F4D	J79-15	3.08	3.38	3.09	1.72	1.21	2.40
F4E	J79-17	2.01	2.27	2.54	1.62	1.23	2.83
T38	J85-5	1.92	1.79	1.57	.74	.63	1.52
F5E	J85-21	1.82	1.97	2.34	3.36	3.57	3.61
F111A	TF30-3	6.50	5.31	5.34	3.11	2.98	4.10
F111E	TF30-3	5.44	6.45	3.62	2.96	3.42	3.60
FB111	TF30-7	6.16	4.23	3.26	4.36	3.20	3.82
F111D	TF30-9	5.15	3.86	2.87	2.02	2.89	3.85
F111F	TF30-100	2.34	2.46	5.66	3.28	2.11	2.63
B52H	TF33-3	3.58	2.99	3.15	1.63	1.28	4.15
C141	TF33-7	2.62	2.73	2.86	1.40	1.79	4.12
E3A	TF33-100	.37	.83	.78	.60	.70	.55
A10	TF34-100	1.23	1.37	1.32	.64	.98	1.44
C5A	TF39-1A	8.90	8.79	7.92	7.12	9.07	10.39
A7D	TF41-1A	1.17	1.30	1.20	1.23	1.22*	1.67
F15	F100-100	3.98	4.14	5.46	1.74	1.69	4.69
F15C	F100-100	-	.46	3.49	2.31	3.48	3.44
F16A	F100-200	-	3.76	3.05	1.80	1.09	2.23

* adjusted due to missing/incorrect data

MMHs/Engine Flying Hours

Aircraft	Engine	78	79	80	81	82	83
B52D	J57-19/29	.69	.60	.59	.42	.18	.09
B52G	J57-43	.60	.47	.45	.14	.47	.49
KC135A	J57-59	.38	.36	.36	.05	.37	.38
T39	J60-3	.66	.60	.34	.47	.47	.53
F106	J75-17	2.20	2.16	2.06	1.96	2.16	2.58
F105	J75-19	4.21	2.60	4.12	2.23	2.03	.91
F4D	J79-15	1.54	1.69	1.55	.86	.61	1.20
F4E	J79-17	1.01	1.14	1.27	1.31	.62	1.42
T38	J85-5	.96	.90	.79	.37	.32	.76
F5E	J85-21	.91	.99	1.17	1.68	1.79	1.81
F111A	TF30-3	3.25	2.66	2.67	1.56	1.49	2.05
F111E	TF30-3	2.72	3.23	1.81	1.48	1.71	1.80
FB111	TF30-7	3.08	2.12	1.63	2.18	1.60	1.91
F111D	TF30-9	2.58	1.93	1.44	1.01	1.45	1.93
F111F	TF30-100	1.17	1.23	2.83	1.64	1.06	1.32
B52H	TF33-3	.45	.37	.39	.20	.16	.52
C141	TF33-7	.66	.68	.72	.35	.45	1.03
E3A	TF33-100	.09	.21	.20	.15	.18	.14
A10A	TF34-100	.62	.69	.66	.32	.49	.72
C5A	TF39-1A	2.23	2.20	1.98	1.78	2.27	2.60
A7D	TF41-1A	1.17	1.30	1.20	1.23	1.22	1.67
F15	F100-100	1.99	2.07	2.73	.87	.85	2.35
F15C	F100-100	-	.23	1.75	1.16	1.74	1.72
F16A	F100-200	-	3.76	3.05	1.80	1.09	2.23

A/C Flying Hours

A/C	78	79	80	81	82	83
B52D	31444	30292	31182	24624	23321	6921
B52G	63152	61672	63040	65119	63257	62409
KC135	215172	206852	215848	216742	212329	195746
T39	97776	79292	83704	78758	84734	79051
F106	63640	67528	58636	61385	56191	51253
F105	33464	34076	26732	18629	9470	4622
F4D	96552	89944	92604	87182	83003	77544
F4E	147832	135392	107304	113190	110363	121375
T38	343970	339876	341217	314253	335896	343435
F5E	25500	26404	26712	28114	26606	26644
F111A	17828	17628	17964	18231	15461	14634
F111E	19100	18776	19044	19708	20629	20303
FB111	18652	17200	16528	16936	17037	17971
F111D	18632	19092	16516	17833	17016	18827
F111F	17124	19684	18184	22591	24229	23028
B52H	35772	35204	36632	38863	37523	36326
C141	266960	280096	291580	288291	285406	285517
E3A	5272	11756	19124	24419	27392	32033
A10	54840	87260	141716	175175	223867	227761
C5	48516	51516	55580	53471	52197	56040
A7D	94040	87028	93716	80694	83920	75053
F15	75328	95720	83684	84192	79151	83920
F15C	-	8944	30580	45451	61186	76657
F16A	-	7156	25540	46599	86760	128881

Appendix B: Engine Variables

Engine	Max Thrust	Max SFC	Max TIT	Norm Thrust	Norm SFC	Airflow	CPR
J57-19/29	10500	.795	1600	9000	.959	165	11.3
J57-43	11200	.775	1600	9500	.765	180	12
J57-59	11200	.775	1600	9500	.765	180	12
J60-3	3000	.96	1600	2570	.905	50	7
J75-17	24500	2.15	1610	14300	.79	252	11.9
J75-19	24500	2.15	1610	14300	.79	252	11.9
J79-15	17000	1.945	1775	10300	.83	169	12.9
J79-17	17900	1.965	1810	11100	.81	170	13.5
J85-5	3850	2.2	1640	2050	.96	44	7
J85-21	5100	2.13	1790	3280	.98	52	8
TF30-3a	18500	2.5	1970	9800	.607	235	17
TF30-3b	18500	2.5	1970	9800	.607	235	17
TF30-7	20350	3.013	2070	10800	.631	242	17.5
TF30-9	20840	2.615	2080	10600	.625	243	18
TF30-100	25100	2.45	2045	13170	.645	260	21.8
TF33-3	16500	.52	1600	14500	.505	450	13
TF33-7	19000	.53	1750	18000	.520	498	16
TF33-100	21000	.56	1750	18000	.520	498	16
TF34-100	9065	.37	2234	7335	.354	333	19.8
TF39-1A	40805	.315	2350	39767	.313	1549	22.1
TF41-1A	14500	.647	2157	13200	.629	260	21
F100-100c	23840	2.17	2565	12410	.69	228	24.9
F100-100d	23840	2.17	2565	12410	.69	228	24.9
F100-200	23840	2.17	2565	12412	.69	228	24.9
Mean	17685	1.60	1929	12004	.691	292	15.9
F101-102	30750	2.775	2550	15470	.54	352	26.5

Notes:
a F111A application
b F111E application
c F15A,B application
d F15C application

Source: "Engine Handbook"

Engine Variables

Engine	Weight	Length	Diameter	Comp.	Turb.
J57-19/29	4150	157.7	40.5	16	3
J57-43	3870	167.3	38.9	16	3
J57-59	4320	167.3	38.9	16	3
J60-3	460	79.5	23.4	9	2
J75-17	5875	237.6	43	15	3
J75-19	5950	259.3	43	15	3
J79-15	3685	208.3	35.2	17	3
J79-17	3685	208.3	39.1	17	3
J85-5	584	109.1	20.4	8	2
J85-21	667	116	20	9	2
TF30-3a	4062	241.7	49	16	4
TF30-3b	4062	241.7	49	16	4
TF30-7	4121	241.4	50.7	16	4
TF30-9	4070	241.7	49	16	4
TF30-100	3985	241.7	48.9	16	4
TF33-3	3905	136.3	53.1	15	4
TF33-7	4612	142.3	54.1	16	4
TF33-100	4790	142.3	54.0	16	4
TF34-100	1421	100	50	15	6
TF39-1A	7186	203.1	100	17.5	8
TF41-1A	3175	114.2	39.2	16	4
F100-100c	3021	198	46.5	13	4
F100-100d	3021	198	46.5	13	4
F100-200	3066	198	46.5	13	4
Mean	3656	181.3	45	14.7	3.7
F101-102	4372	180.7	55.2	11	3

Notes: a F111A application
b F111E application
c F15A,B application
d F15C application

Source: "Engine Handbook"

Appendix C: Regression of Complete Data Set

regress(X9,Y)

	Coef	Std Err	t value
intercept	-0.7174456	0.3805603	-1.885235
X9	0.0113230	0.0020149	5.619437

Std Err 0.522412 R^2 0.589384
F 31.57807 on 1, 22 df

regress(X11,Y)

	Coef	Std Err	t value
intercept	0.4018338	0.5622211	0.714726
X9	0.0140682	0.0021129	6.652064
X11	-0.1100921	0.0439130	-2.507070

Std Err 0.469094 R^2 0.683972
F 22.72486 on 2, 21 df

regress(X21,Y)

	Coef	Std Err	t value
intercept	0.3771140	0.5051452	0.746546
X9	0.0146817	0.0019166	7.662029
X11	-0.1663933	0.0456320	-3.646416
X12	0.1996646	0.0813526	2.454382

Std Err 0.4213883 R^2 0.7571253
F 20.78233 on 3, 20 df

regress(X31,Y)

	Coef	Std Err	t value
intercept	0.2214503	0.5364837	0.412781
X9	0.0153609	0.0020692	7.423619
X10	-0.0157725	0.0175858	-0.896888
X11	-0.1559034	0.0473248	-3.294326
X12	0.3508762	0.1946255	1.839821

Std Err o.423464 R^2 0.766990
F 15.63542 on 4, 19 df

regress(X41,Y)

	Coef	Std Err	t value
intercept	0.6666639	0.6061742	1.0997890
X2	0.6631909	0.0918219	7.2225730
X8	0.0006389	0.0001409	4.5335850
X10	-0.0762969	0.0263889	-2.8912480
X11	-0.1865237	0.0538826	3.6551410
X12	0.9281116	0.2539195	3.6551410

Std Err 0.363631 R^2 0.837227
F 18.51674 on 5, 18 df

regress(X51,Y)

	Coef	Std Err	t value
intercept	1.0858580	0.5751945	1.8878100
X4	0.0000491	0.0000386	1.2732410
X8	0.0002811	0.0001779	1.5802560
X9	0.0150113	0.0021642	6.9360140
X10	-0.0912167	0.0288267	-3.1643090
X11	-0.2201559	0.0584689	-3.7653540
X12	0.8748143	0.2508574	3.4872960

Std Err 0.358998 R^2 0.850163
F 16.07606 on 6, 17 df

regress(X61,Y)

	Coef	Std Err	t value
intercept	-0.0290271	0.5411703	-0.0536377
X1	-0.0001922	0.0000871	-2.2074840
X4	0.0004046	0.0001576	2.5674290
X6	-0.0052557	0.0029277	-1.7950990
X9	0.0292536	0.0058434	5.0062370
X10	-0.0643898	0.0290976	-2.2128880
X11	-0.3378470	0.0972872	-3.4726750
X12	1.0769880	0.2798838	3.8479700

Std Err 0.3458181 R^2 0.869141
F 15.18131 on 7, 16 df

regress(X71,Y)

	Coef	Std Err	t value
intercept	-1.2750620	0.6896763	-1.8487830
X1	-0.0002698	0.0000862	-3.1278480
X4	0.0008549	0.0002090	4.0890980
X6	-0.0172474	0.0041742	-4.1318670
X7	-0.1632236	0.0572209	-2.8525170
X8	-0.0004478	0.0002095	-2.1372080
X9	0.0348371	0.0066828	5.2129080
X11	-0.4824412	0.0919024	4.3104850

Std Err 0.3272487 R^2 0.890141
F 15.19238 on 8, 15 df

regress(X81,Y)

	Coef	Std Err	t value
intercept	-1.5798700	0.7243359	-2.1811290
X1	-0.0002730	0.0000850	-3.2122630
X2	0.3755255	0.3101018	1.2109750
X4	0.0008525	0.0002059	4.1407550
X6	-0.0172770	0.0041108	-4.2027620
X7	-0.1624343	0.0563551	-2.8823320
X8	-0.0003011	0.0002392	-1.2588600
X9	0.0274436	0.0089772	3.0570410
X11	-0.4531900	0.0936738	-4.8379560
X12	1.9718840	0.4421047	4.4602190

Std Err 0.322276 R^2 0.900558
F 14.08724 on 9, 14 df

regress(X91,Y)

	Coef	Std Err	t value
intercept	-0.2910432	1.7408950	-0.1671802
X1	-0.0002126	0.0000868	-2.4492550
X3	0.0016646	0.0011593	1.4374720
X4	0.0005849	0.0001678	3.4853310
X5	-1.8975750	1.2527620	-1.5147120
X6	-0.0105841	0.0038398	-2.7564150
X7	-0.1739217	0.0910987	-1.0901560
X9	0.0292837	0.0062971	4.6503660
X10	-0.0491297	0.0328889	-1.4938050
X11	-0.3860686	0.1034882	-3.7305530
X12	1.3164290	0.4017824	3.2764730

Std Err 0.3243665 R^2 0.906459
F 12.59763 on 10,13 df

regress(X101,Y)

	Coef	Std Err	t value
intercept	-0.6677251	1.8437640	-0.3621533
X1	-0.0002284	0.0000909	-2.5126840
X2	0.2482215	0.3355907	0.7396556
X3	0.0013357	0.0012618	1.0585540
X4	0.0006443	0.0001887	3.4133810
X5	-1.5549410	1.3567040	-1.1461160
X6	-0.0120607	0.0043888	-2.7480410
X7	-0.1726562	0.0927441	-1.8616400
X9	0.0257192	0.0080193	3.2071730
X10	-0.0390297	0.0361551	-1.0795060
X11	-0.3878417	0.1053667	-3.6808730
X12	1.4719330	0.4598435	3.2009440

Std Err 0.330169 R^2 0.910538
F 11.10313 on 11, 12 df

regress(X111,Y)

	Coef	Std Err	t value
intercept	-0.7848970	1.9322540	-0.4062079
X1	-0.0002578	0.0001183	-2.1785400
X2	0.2211193	0.3540420	0.6245570
X3	0.0011574	0.0013780	0.8399462
X4	0.0007578	0.0003384	2.2392720
X5	-1.5412010	1.4066650	-1.0956420
X6	-0.0144856	0.0074485	-1.9447580
X7	-0.1905115	0.1054871	-1.8060170
X8	-0.0001589	0.0003866	-0.4111346
X9	0.0289880	0.0115025	2.5201340
X10	-0.0265784	0.0481863	-0.5516033
X11	-0.4200792	0.1344487	-3.1244570
X12	1.6193230	0.5964127	2.7151960

Std Err 0.3422307 R^2 0.911891
F 9.48717 on 12, 11 df

Appendix D: Complete Data Test Cases

$$X41 = .667 + .663X2 + .001X8 - .076X10 - .187X11 + .928X12$$

$$F100 = .667 + 1.439 + 3.021 - 3.534 - 2.431 + 3.712$$
$$= 2.874$$

$$F101 = .667 + 1.839 + 4.372 - 4.195 - 2.057 + 2.784$$
$$= 3.410$$

$$Mean = .667 + 1.060 + 3.656 - 3.416 - 2.747 + 3.441$$
$$= 2.661$$

$$X71 = -1.2751 - .003X1 + .009X4 - .0172X6 - .1632X7$$
$$- .004X8 + .0348X9 - .4824X11 + 1.9288X12$$

$$F100 = -1.2751 - 7.152 + 11.169 - 3.9216 - 4.0637$$
$$- 1.2084 + 6.8904 - 6.2712 + 7.7152$$
$$= 1.8826$$

$$F101 = -1.2751 - 9.225 + 13.923 - 6.0544 - 4.3248$$
$$- 1.7488 + 6.2884 - 5.302 + 5.7864$$
$$= - 1.9323$$

$$\begin{aligned}\text{Mean} &= -\,1.2751 - 5.2946 + 10.8038 - 5.0174 - 2.5935 \\ &\quad - 1.4624 + 6.3092 - 7.0853 + 7.1526 \\ &= 1.5373\end{aligned}$$

Appendix E: Regression of Reduced Variables

regress(X2,Y)

	Coef	Std Err	t value
intercept	0.3796986	0.2646577	1.4346780
X2	0.5977129	0.1457940	4.0997090

Std Err 0.61383 R^2 0.433101
F 16.80761 on 1, 22 df

regress(X24,Y)

	Coef	Std Err	t value
intercept	-6.1784e-1	0.3019997	-2.0454885
X2	7.6366e-1	0.1147628	6.6542810
X4	6.0994e-5	0.0000140	4.3494810

Std Err 0.455696 R^2 0.701766
F 24.7073 on 2, 21 df

regress(X126,Y)

	Coef	Std Err	t value
intercept	-0.4392676	0.2793559	-1.5724300
X1	0.0000353	0.0000226	1.5610280
X2	0.6245521	0.1707595	3.6574950
X6	0.0005147	0.0007134	0.7215184

Std Err 0.464359 R^2 0.7050663
F 15.93729 on 3, 20 df

regress(X1237,Y)

	Coef	Std Err	t value
intercept	-1.2815400	0.8546913	-1.4994190
X1	6.4765e-5	0.0000165	3.9189080
X2	4.7596e-1	0.1180400	4.0321540
X3	1.0355e-3	0.0007970	1.2990960
X7	-8.1006e-2	0.0547837	-1.4786550

Std Err 0.4569063 R^2 0.728734
F 12.7605 on 4, 19 df

regress(X12347,Y)

	Coef	Std Err	t value
intercept	-1.2882860	0.8776326	-1.4679110
X1	0.0000783	0.0000670	1.1686830
X2	0.4158567	0.3112853	1.3359340
X3	0.0011285	0.0009306	1.2126710
X4	-0.0000146	0.0000697	-0.2095852
X7	-0.0899101	0.0704638	-1.2759760

Std Err 0.468855 R^2 0.729394
F 9.7035 on 5, 18 df

regress(X123567,Y)

	Coef	Std Err	t value
intercept	-1.0157920	1.1398970	-0.8911264
X1	0.0000900	0.0000459	1.9609230
X2	0.3649200	0.2556631	1.4273470
X3	0.0017094	0.0013014	1.3137010
X5	-0.8773564	1.3068020	-0.6713763
X6	-0.0008367	0.0013160	-0.6357705
X7	-0.1430099	0.1059237	-1.3501210

Std Err 0.4760325 R^2 0.737543
F 7.92111 on 6, 17 df

regress(XXX,Y)	Coef	Std Err	t value
intercept	-1.1522040	1.2151700	-0.9481829
X1	0.0000636	0.0000796	0.8000111
X2	0.4482509	0.3315757	1.3518800
X3	0.0019799	0.0014880	1.3304970
X4	0.0000624	0.0001520	0.4104556
X5	-1.2538100	1.6238040	-0.7721433
X6	-0.0017757	0.0026560	-0.6685519
X7	-0.1598660	0.1161177	-1.3767570

Std Err 0.48812 R^2 0.7392883
F 6.4815 in 7, 16 df

regress(X9,Y)

	Coef	Std Err	t value
intercept	-0.7174456	0.3805603	-1.885235
X9	0.0113230	0.0020149	5.619437

Std Err 0.522412 R^2 0.589384
F 31.57807 on 1, 22 df

regress(X911,Y)

	Coef	Std Err	t value
intercept	0.4018338	0.5622211	0.7147260
X9	0.0140682	0.0021148	6.6520640
X11	-0.1100921	0.0439130	-2.5070500

Std Err 0.469094 R^2 0.683972

F 22.72486 On 2, 21 df

regress(X912,Y)

	Coef	Std Err	t value
intercept	0.3771140	0.5051452	0.7465460
X9	0.0146816	0.0019161	7.6620290
X11	-0.1663933	0.0456302	-3.6464160
X12	0.1996646	0.0813502	2.4543820

Std Err 0.4213883 R^2 0.7571253

F 20.78233 on 3, 20 df

regress(X912a,Y)

	Coef	Std Err	t value
intercept	0.2214503	0.5364837	0.4127811
X9	0.0153609	0.0020692	7.4236190
X10	-0.0157725	0.0175858	-0.8968886
X11	-0.1559034	0.0473248	-3.2943260
X12	0.3580762	0.1946255	1.8398210

Std Err 0.423464 R^2 0.766990

F 15.63542 on 4, 19 df

regress(XX4,Y)

	Coef	Std Err	t value
intercept	1.1826450	0.5799032	2.0393830
X8	0.0004096	0.0001490	2.7485630
X9	0.0136085	0.0018947	7.1824050
X10	-0.0755291	0.0265068	-2.8494240
X11	-0.2520290	0.0537429	-4.6895320
X12	0.8857785	0.2549986	3.4736600

Std Err 0.3651395 R^2 0.835874

F 18.33436 on 5, 18 df

Appendix F: Reduced Variables Test Cases

$$X24 = - .6178 + .763X2 + .00006X4$$

$$F100 = - .6178 + 1.657 + .7446$$
$$= 1.784$$

$$F101 = - .6178 + 2.119 + .9282$$
$$= 2.429$$

$$Mean = - .6178 + 1.221 + .7203$$
$$= 1.324$$

$$XX4 = 1.1826 + .0004X8 + .0136X9 - .0755X10$$
$$- .252X11 + .8858X12$$

$$F100 = 1.1826 + 1.2084 + 2.6928 - 3.5108$$
$$- 3.276 + 3.5432$$
$$= 1.8402$$

$$F101 = 1.1826 + 1.7488 + 2.4575 - 4.1676$$
$$- 2.772 + 2.6574$$
$$= 1.1067$$

$$\begin{aligned} \text{Mean} &= 1.1826 + 1.4624 + 2.4657 - 3.3939 \\ &\quad - 3.7013 + 3.2848 \\ &= 1.3003 \end{aligned}$$

Appendix G: Regression of Reduced Samples

regress(b41,yfat)

	Coef	Std Err	t value
intercept	-2.9155830	0.7309118	-3.9889700
X1	-0.0005132	0.0000678	-7.5626800
X3	0.0016801	0.0003114	5.3939000
X4	0.0007509	0.0000893	8.4006200
X9	0.0456726	0.0050715	9.0057000
X11	-0.4425207	0.0494313	-8.9522300

Std Err 0.1654703 R^2 0.954543
F 33.5983 on 5, 8 df

regress(d41,ypwa)

	Coef	Std Err	t value
intercept	1.8603930	0.4018036	4.6301060
X1	-0.0002042	0.0000402	-5.0751760
X4	0.0002496	0.0000474	5.2559060
X9	0.0371565	0.0037464	9.9178000
X10	0.0312968	0.0135496	2.3097960
X11	-0.5545818	0.0721928	-7.6819500

Std Err o.1748457 R^2 0.973749
F 81.6055 on 5, 11 df

Appendix H: Reduced Samples Test Cases

$$b41 = -\ 2.9156 - .0005X1 + .0017X3 + .0008X4$$
$$+\ .045X9 - .4425X11$$

$$F100 = -\ 2.9156 - 11.92 + 4.3605 + 9.928$$
$$+\ 9.0486 - 5.7525$$
$$= \ 2.749$$

$$Mean = -\ 2.9156 - 8.823 + 3.280 + 9.6034$$
$$+\ 8.254 - 6.4992$$
$$= \ 2.912$$

841 = 1.8604 - .0002X1 + .00025X4 + .0372X9

+ .0313X10 - .5546X11

F100 = 1.8604 - 4.768 + 3.1025 + 7.3656

+ 1.4555 - 7.2098

= 1.8062

F101 = 1.8604 - 6.15 + 3.8675 + 6.7220

+ 1.7278 - 6.1006

= 1.9271

Mean = 1.8604 - 3.569 + 3.001 + 6.7444

+ 1.407 - 8.1457

= 1.3302

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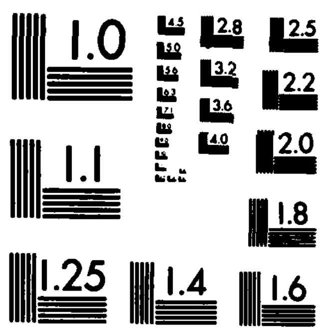
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An accurate technique for estimating propulsion system maintenance manhours would be a useful tool for the USAF. Accurate projections early in the acquisition of a program can influence design and provide significant life-cycle cost savings. Propulsion systems, or engines, have very large operating and support costs and any improvements gained early in the life cycle could reap great benefits.

Cost-estimating relationships (CERs) have been used on other systems and items to project cost and will be applied here to engines. Various performance and physical parameters of a large sample of USAF engines were utilized to develop CERs to estimate future maintenance manhour requirements. A number of potential CERs were developed in the study which displayed sufficient accuracy to be considered for application on acquisition programs.

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